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N64-16703

MTP-P&VE-M-63-18 OTS: $ ---
December 7, 1963

NASA.

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HUNTSVILLE, ALABAMA

THE EFFECT OF SOLIDIFICATION RATE ON THE BETA PHASE IN 5456 ALUMINUM ALLOY

by

H. H. Kranzlein

(NASA TMX 54616; 7 Dec. 1963 27p refs

OTS PRICE

XEROX $ 2.60 ph

MICROFILM $ 1.01 mf

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ABSTRACT

A

The presence of beta phase (Mg_5Al_8) in the microstructure of welded 5456 aluminum alloy may be detrimental to the strength and corrosion properties of the welds. In the investigation covered by this report, the influence of solidification rate on the quantity, distribution, and particle size of the beta phase was established to determine if control of the phase is feasible through regulation of the solidification rate. Experiments with small castings indicate that limited control of the quantity and distribution of the beta phase is possible.

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THE EFFECT OF SOLIDIFICATION RATE ON THE BETA PHASE IN 5456 ALUMINUM ALLOY

By

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SUMMARY

The effect of solidification rate on the quantity, distribution and particle size of the beta phase in 5456 aluminum alloy was determined. Experiments with 50 gram castings indicate that the quantity of beta phase decreased with decreasing solidification rate while the particle size and spacing increased. As much as 7.3 volume percent of the beta phase was observed in castings cooled through the solidification temperature range at a rate of 18°C per second (18°C/sec). In the fusion zone of a welded three-fourth inch 5456 plate, 8 to 9 volume percent of the beta phase was observed. On the basis of experiments with small 5456 castings, it appears that the quantity of beta phase in welds could be reduced to 3.5 to 4.5 volume percent by cooling through the solidification range at a rate of 4 to 6°C/sec.

the approximate fraction of liquid present at any temperature during solidification. Knowledge of the fraction of liquid remaining at any temperature permits, through application of the lever law, calculation of the nonequilibrium solidus for an alloy of a given composition.

$$f_L = \left(\frac{X_o}{X_L}\right)^{X_L/X_L - X_s} \qquad \text{Equation (1)}$$

where: f_L = fraction of liquid present at any temperature during nonequilibrium solidification
X_o = initial concentration of solute in melt
X_L = concentration of solute in liquid at temperature
X_s = concentration of solute in solid at temperature

It should be noted that certain assumptions are inherent in the application of this equation. (1) It is assumed that diffusion in the solid is negligible. This is a valid assumption, particularly in the case of alloys solidifying as rapidly as weld deposits. (2) It is assumed that diffusion is complete in the liquid. (3) The composition of the solid formed on cooling through any infinitesimal temperature interval is given by the solidus of the phase diagram. This assumption is fundamental to phase diagram interpretation in general. (4) It is assumed that the liquidus and solidus of the binary system approximate straight lines. Reference to FIG 1 will show this to be a reasonable approximation in the case of the Al-Mg system.

Equation (1) was evaluated for the case of an aluminum-5% magnesium alloy at temperatures of 450, 500 and 550°C (842, 932 and 1022°F). The calculated fractions of liquid present at each of these temperatures, as the result of nonequilibrium solidification, are given below:

Temp. °C	f_L
450	.020
500	.046
550	.115

were etched lightly with a modified Keller's reagent to reveal the phases. Analyses of the quantity and distribution of phases in the castings were made by standard quantitative metallographic procedures (Ref. 5). Since the alpha phase of the eutectic could not be distinguished from the primary alpha, all quantitative measurements relate only the amount of beta phase in the alloy castings.

Point counting was used to determine the quantity of beta phase present in the castings. A grid was superimposed over the ground glass plate of a metallograph, the specimen microstructure was projected onto the ground glass at a magnification of 750x,and the number of grid intersections falling on the beta phase was counted. The volume fraction of beta phase was then calculated from Equation (2)

$$f_v = N_p / N_t \qquad \text{Equation (2)}$$

where: f_v = volume fraction
N_p = number of grid intersections falling over beta phase
N_t = total number of grid intersections

Point counts were made on 10 different areas of each sample in the vicinity of the thermocouple, and the results were averaged.

Beta phase particle spacing was determined by a linear intercept method. Random lines of known length were superimposed over the microstructure, and the number of beta phase particles intersecting the lines was counted. The number of particles per unit length (p_L) was calculated, and the average particle spacing was taken as $1/p_L$. Forty determinations were made on each sample, and the results were averaged.

RESULTS AND DISCUSSION

Solidification data for fifteen 5456 aluminum alloy castings are given in Table 2. The solidification time for these castings ranged from 9 to 519 seconds. These time intervals were based on the time required to cool from the liquidus temperature to the eutectic temperature, 450°C (842°F). The selection of this solidification range was justified since the presence of the alpha plus beta eutectic indicated that solidification was not complete until the eutectic isotherm was reached. Since the temperature measuring system used in this investigation was not sensitive enough to detect the actual eutectic reaction

The results of this investigation demonstrate that the beta phase can be formed in castings of 5456 aluminum alloy as the result of nonequilibrium solidification. It is not unreasonable to assume that the beta phase found in 5456 welds is also due to nonequilibrium solidification.

According to recent welding studies with one-half inch thick 2219 aluminum alloy plate (Ref. 6), welds solidify at rates higher than those used in this study. Solidification indices of 30°C/sec or more for a solidification range of 620 to 450°C (1148 to 842°F) may occur in arc welding.

Metallographic examination of the fusion zone of welded 5456, three-fourth inch thick plate, indicated that approximately 8 to 9 volume percent beta phase was present. This measurement does not include the heavy beta phase formations found in the crown laps of welds, as shown in FIG 9a. FIG 9b illustrates the beta phase formation in the weld fusion zone. Within the fusion zone, the microstructure compared closely with the microstructure of the most rapidly solidified castings prepared in this study. The beta phase particles in the fusion zone were small and dispersed with an average particle spacing of .03mm. The measurements of the volume percent and particle spacing of the beta phase in the fusion zone appear to be consistent with a solidification index of about 30°C/sec.

Beta phase formations like those observed in the crown laps of welds were not observed in any of the castings prepared during this investigation.

Also, it should be noted that the actual quantity of beta phase present in castings and welds was higher than the amount predicted with the aid of Equation (1). On the basis of the observed quantity of beta phase, the apparent nonequilibrium solidus for 5456 castings with a solidification index of 18°C/sec is shown in FIG 10. This discrepancy may be related to errors in the assumptions associated with Equation (1). For example, Tiller et al (Ref. 7) have challenged the assumption that diffusion is complete in the liquid and have stated that diffusion is not rapid enough in the liquid to permit complete diffusion to occur.

It is unlikely that the formation of the beta phase can be avoided in welds. Regulation of solidification rates permits some control of the quantity and distribution of the phase. However, two opposing

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7. Tiller, W. A., Jackson, K. A., Rutter, J. W. and Chalmers, B., "The Redistribution of Solute Atoms During the Solidification of Metals," Acta Metallurgica, 1. 1953, page 428.

8. Hansen, M., Constitution of Binary Alloys, 2nd Ed., McGraw-Hill Book Company, Inc., New York, 1958, page 106.

TABLE II

Solidification Data for 5456 Aluminum Alloy Castings

Trough Mold

Heat No.	Approx. Casting Temp., °C	Mold Temp. °C	Observed Liquidus Temp., °C	Solidification Time sec	Solidification Index °C/sec
ST-8	780	20*	612	9	18.0
ST-10	-	10	610	10	17.6
ST-1	800	30	590	16	9.3
ST-7	810	20	612	19	8.5
ST-2	770	200	590	17	8.2
ST-3	770	300	600	32	4.7
ST-4	800	356	618	40	4.2
ST-5	820	400	614	57	2.9
ST-6	810	442	620	160	1.1
ST-9	890	530	621	519	0.33

Cylindrical Mold

Heat No.	Mold Temp. °C	Observed Liquidus Temp., °C	Solidification Time sec	Solidification Index °C/sec
SC-12	30	614	82	2.0
SC-11	90	616	116	1.4
SC-10	204	618	198	0.85
SC-9	315	616	250	0.66
SC-8	426	618	298	0.56

*Water quenched from 550°C

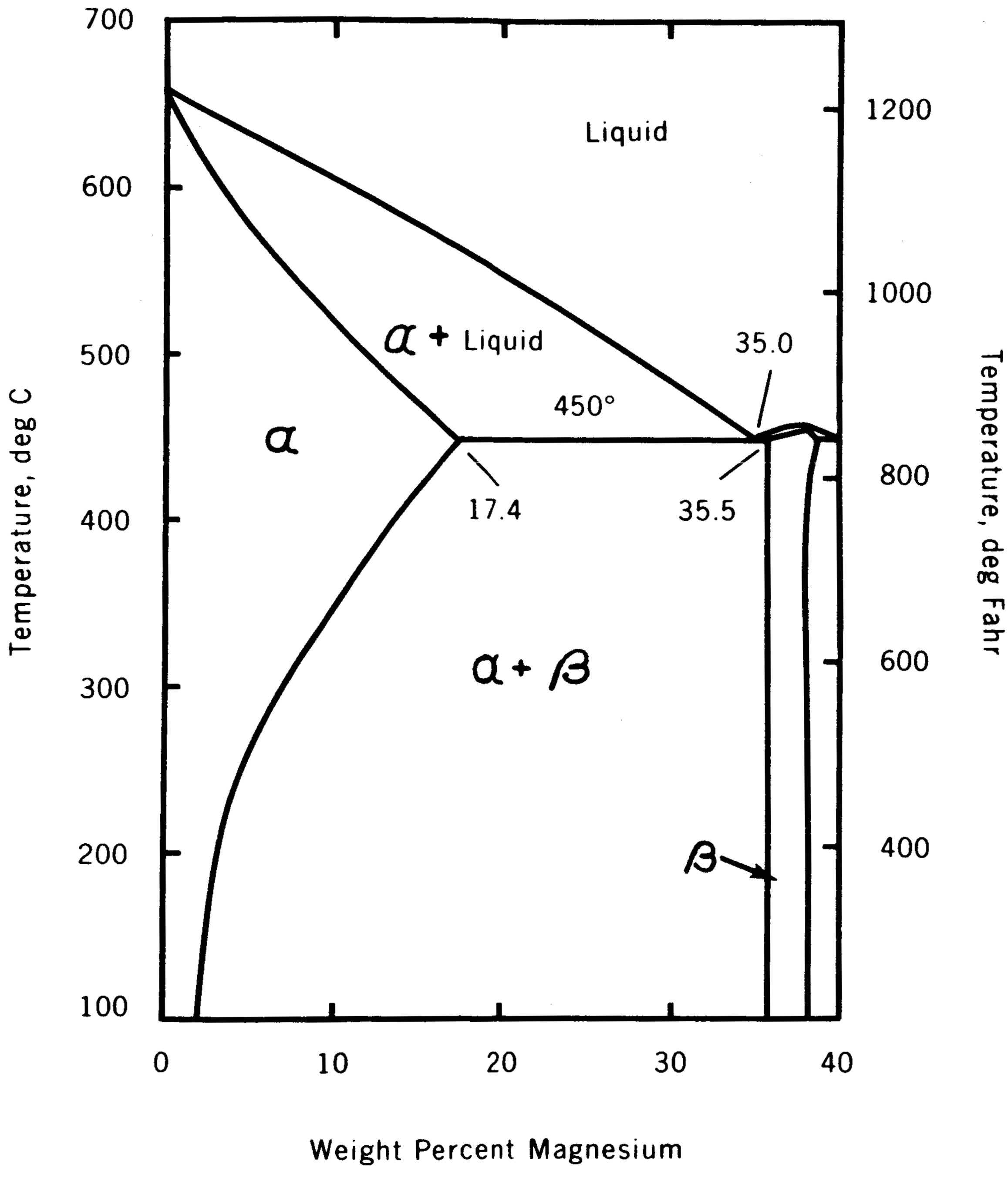


FIGURE 1 PARTIAL ALUMINUM-MAGNESIUM PHASE DIAGRAM (ADAPTED FROM REFERENCE 8)

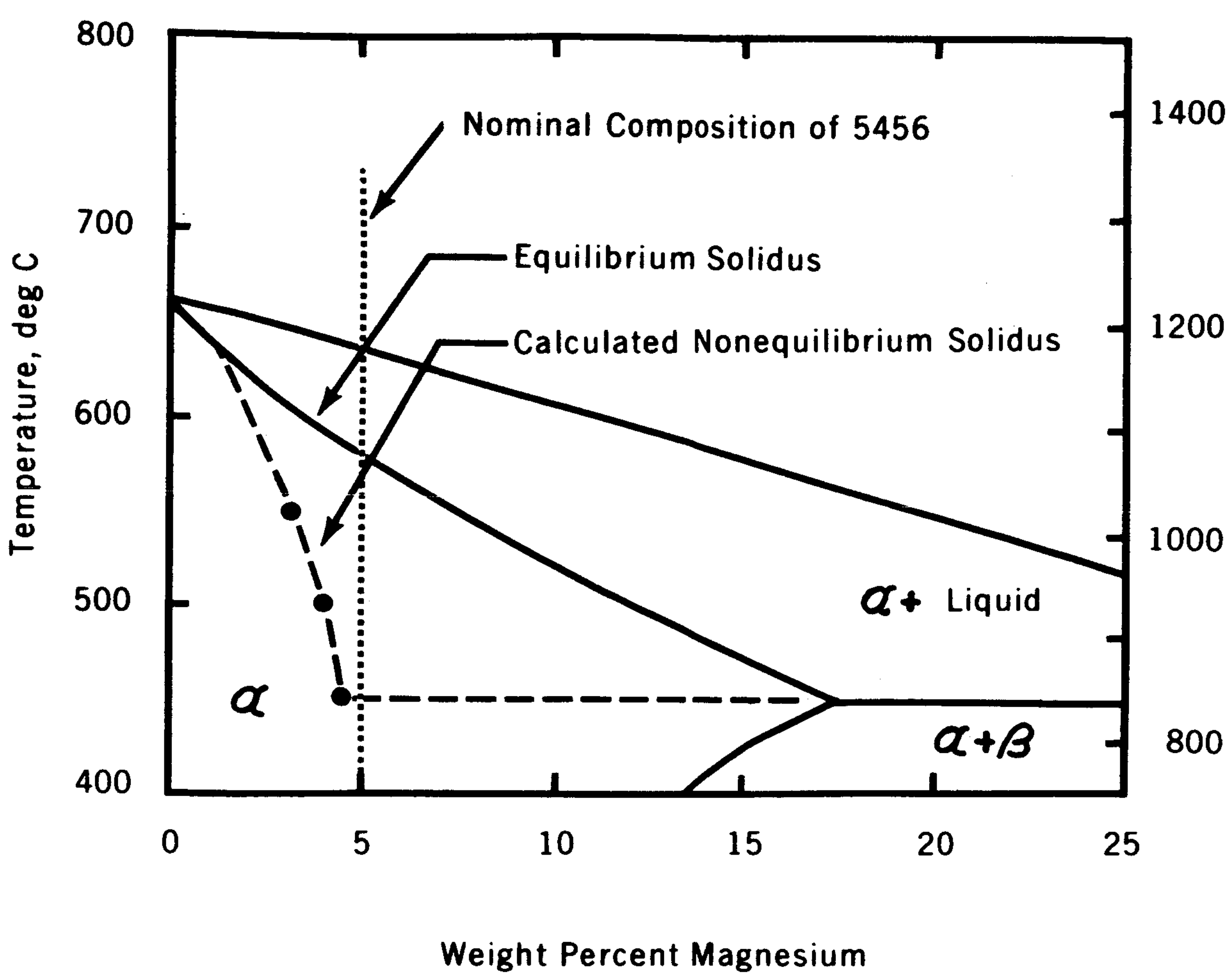


FIGURE 2 CALCULATED NONEQUILIBRIUM SOLIDUS FOR ALUMINUM-5% MAGNESIUM ALLOY

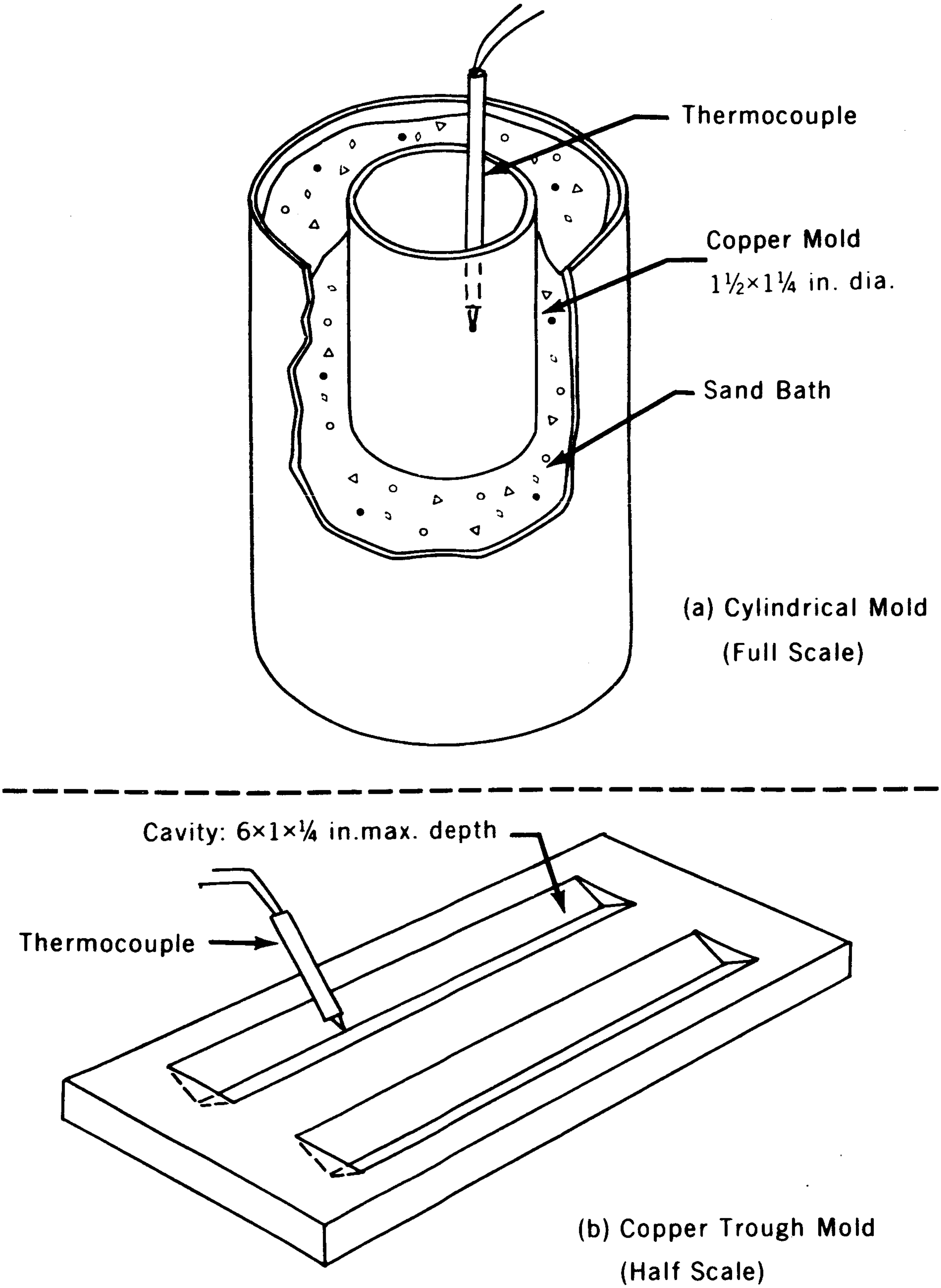
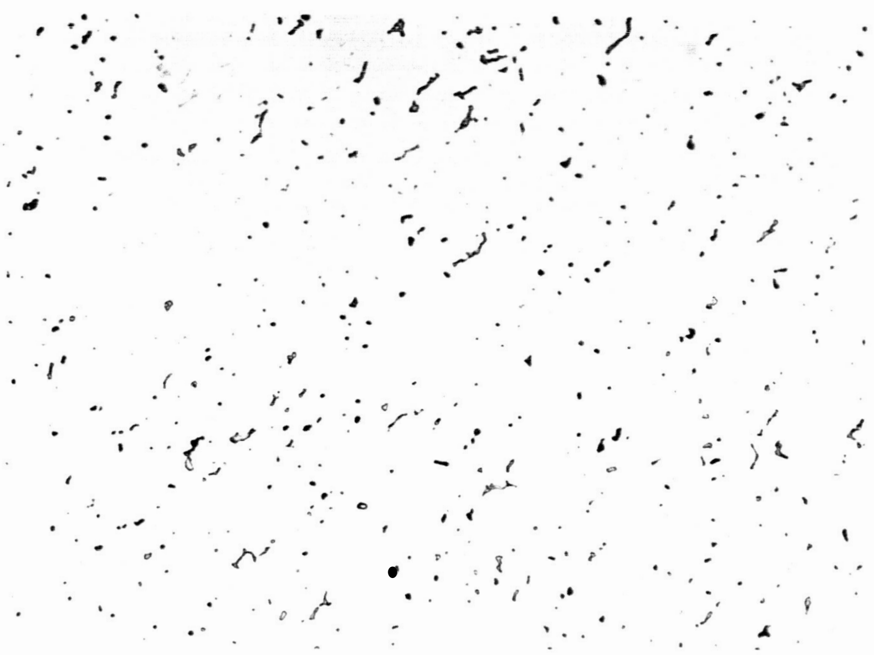


FIGURE 3 MOLD DESIGNS

(a) Solidification Index = 18 deg C/sec

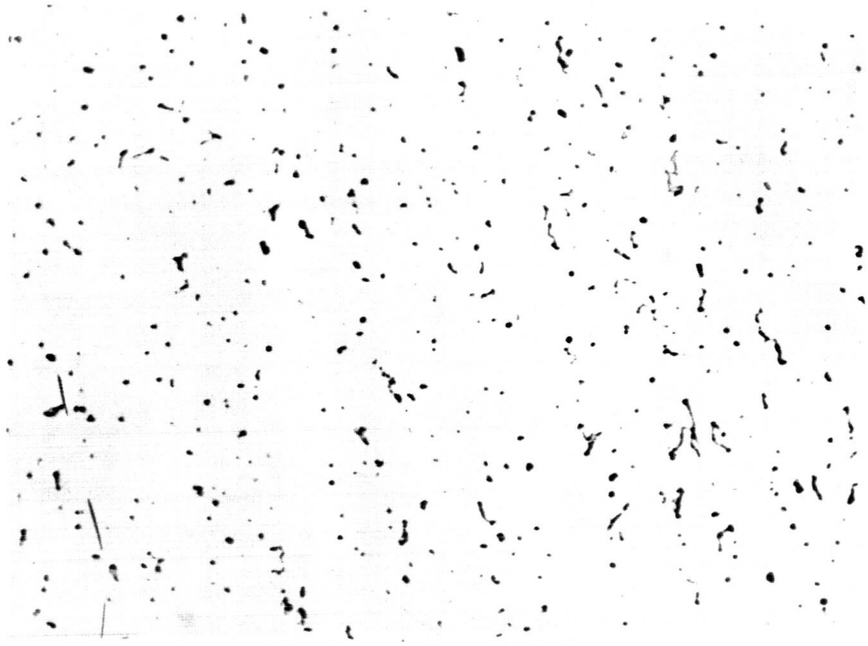
Keller's Etch (Modified) Mag. 200X



(b) Solidification Index = 8.5 deg C/sec

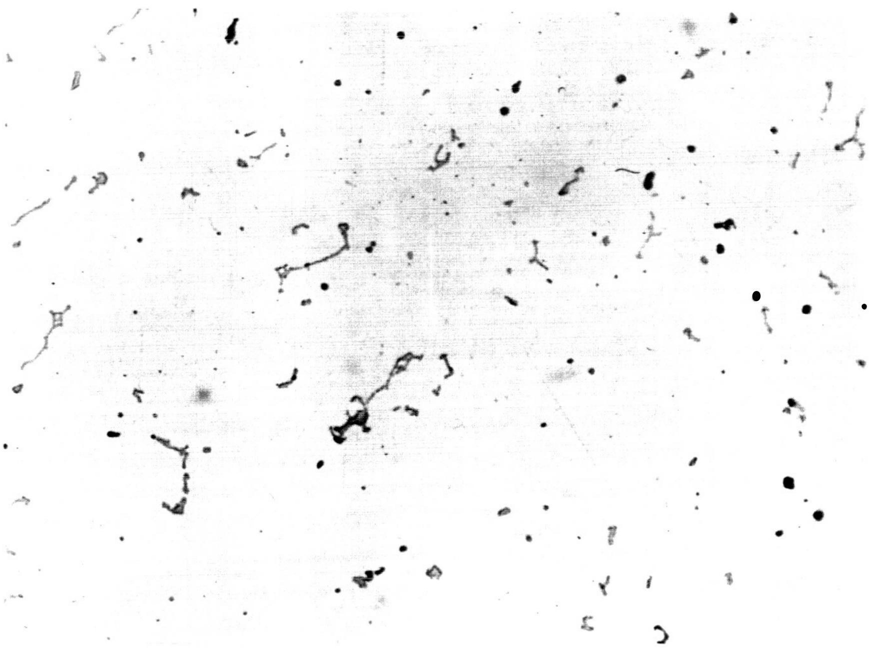
Keller's Etch (Modified) Mag. 200X

FIGURE 4 MICROSTRUCTURE OF CAST 5456 ALUMINUM ALLOY (TROUGH MOLD)



(a) Solidification Index = 4.2 deg C/sec

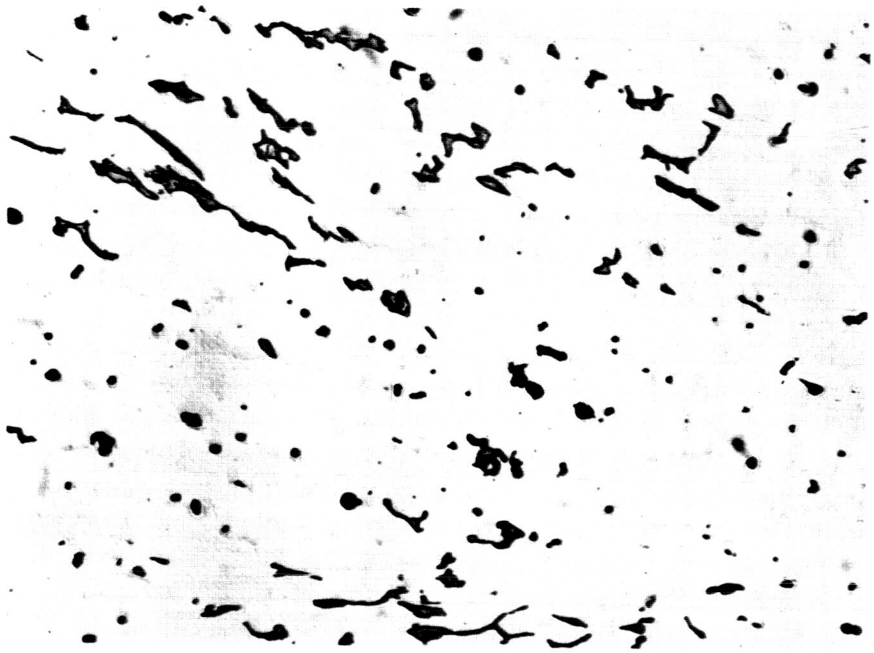
Keller's Etch (Modified) Mag. 200X



(b) Solification Index = 0.33 deg C/sec

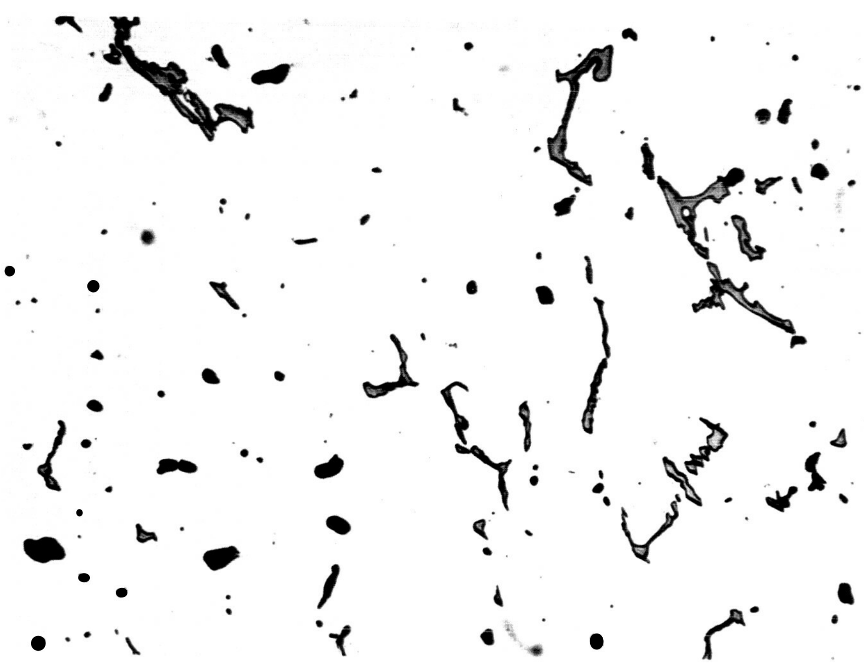
Keller's Etch (Modified) Mag. 200X

FIGURE 5 MICROSTRUCTURE OF CAST 5456 ALUMINUM ALLOY (TROUGH MOLD)



(a) Solidification Index = 1.4 deg C/sec

Keller's Etch (Modified) Mag. 200X



(b) Solidification Index = 0.56 deg C/sec

Keller's Etch (Modified) Mag. 200X

FIGURE 6 MICROSTRUCTURE OF CAST 5456 ALUMINUM ALLOY (CYLINDRICAL MOLD)

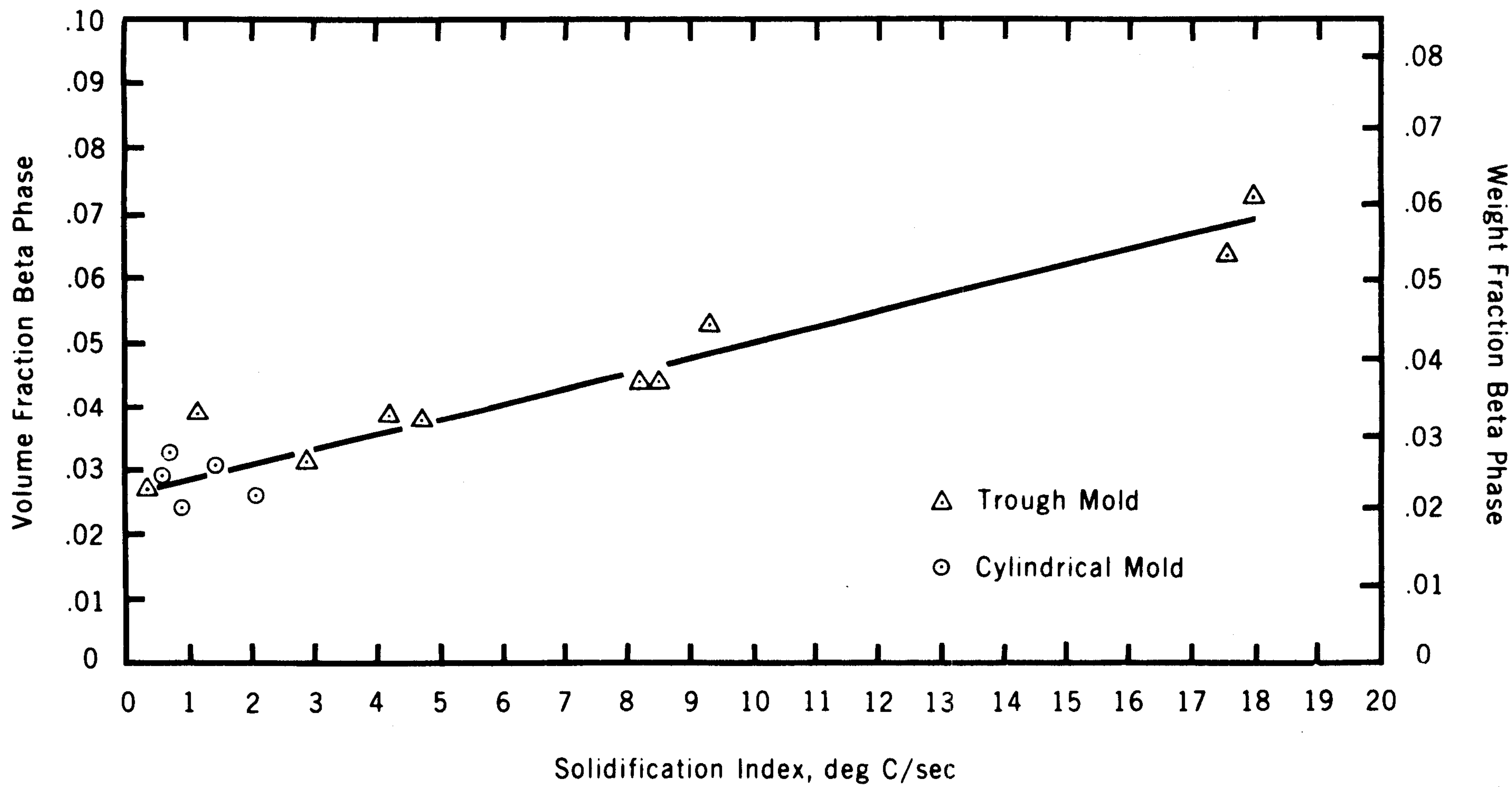


FIGURE 7 VARIATION IN THE QUANTITY OF BETA-PHASE AS A FUNCTION OF SOLIDIFICATION INDEX

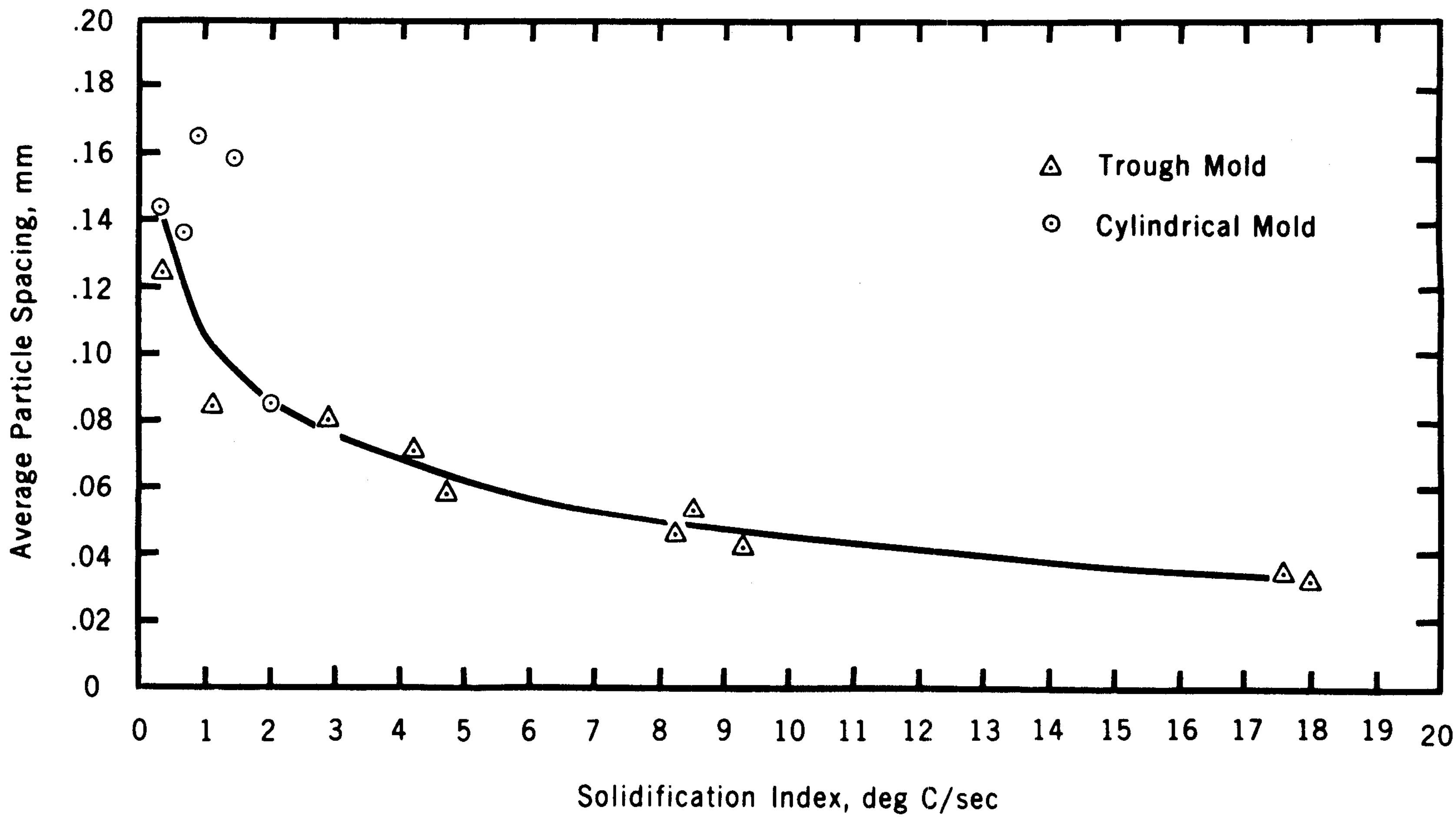
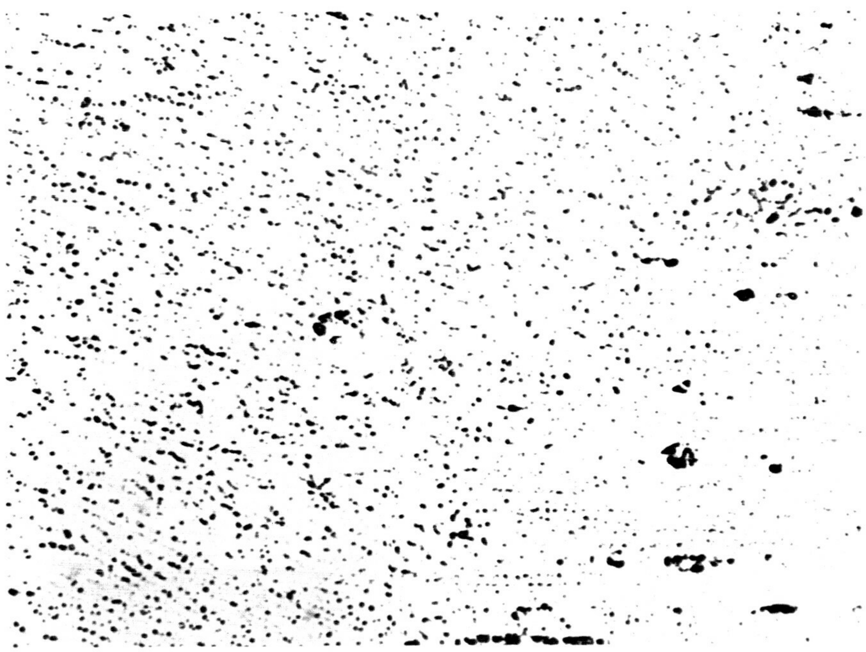


FIGURE 8 VARIATION IN THE AVERAGE DISTANCE BETWEEN BETA-PHASE PARTICLES AS A FUNCTION OF SOLIDIFICATION INDEX

(a) Crown Lap

Keller's Etch (Modified) Mag. 200X



(b) Fusion Zone

Keller's Etch (Modified) Mag. 200X

FIGURE 9 EXAMPLES OF BETA-PHASE FORMATION IN 5456 WELDS

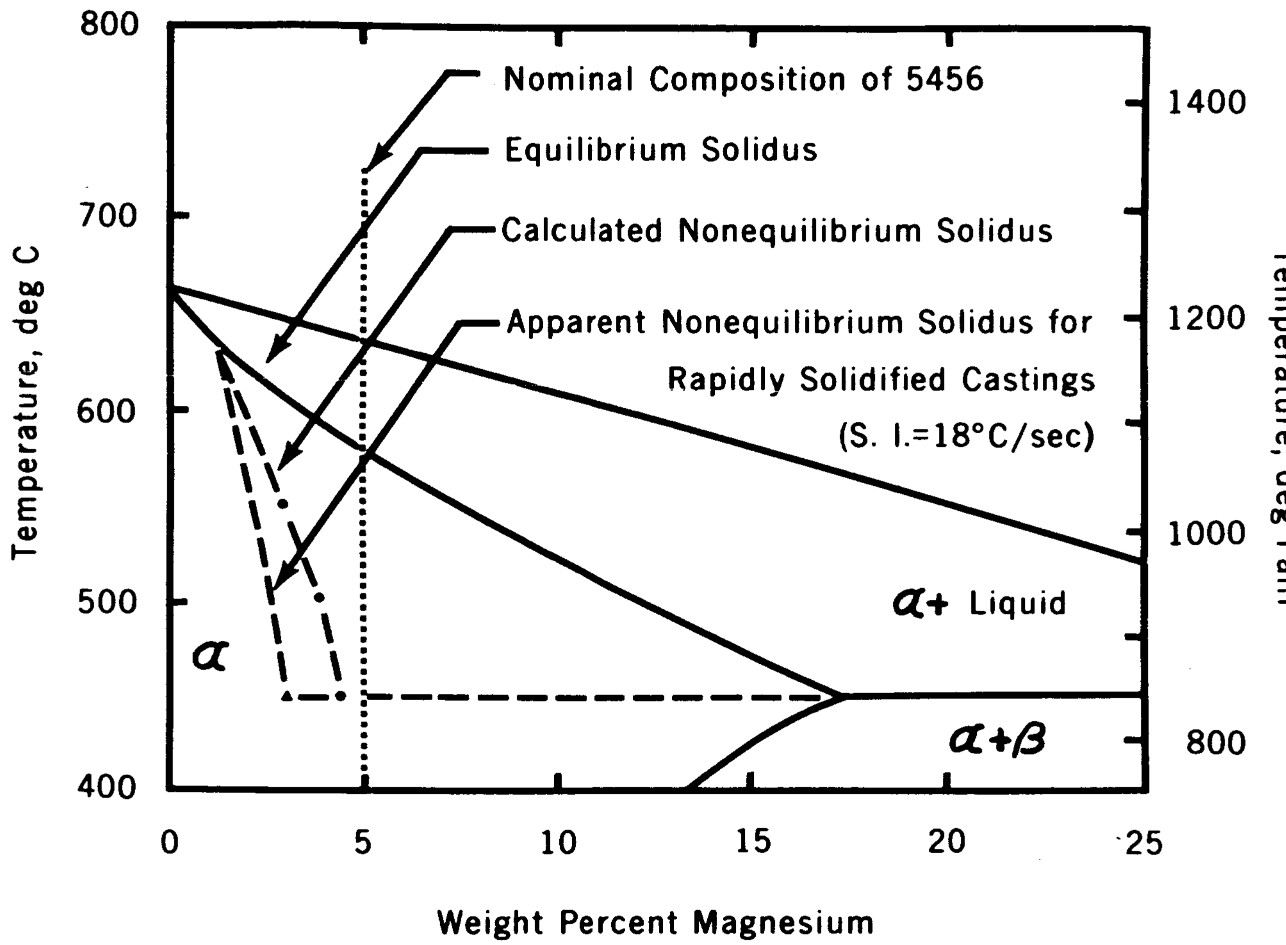


FIGURE 10 NONEQUILIBRIUM SOLIDUS LINES, AS-CALCULATED AND AS-OBSERVED

December 7, 1963 APPROVAL MTP-P&VE-M-63-18

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The information in this report has been reviewed by security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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